

ANISOTROPY IN THE MATTER DISTRIBUTION BEYOND THE BARYONIC
ACOUSTIC OSCILLATION SCALEA. FALTENBACHER¹ AND CHENG LI² AND JIE WANG³*Draft version June 1, 2012*

ABSTRACT

Tracing the cosmic evolution of the Baryonic Acoustic Oscillation (BAO) scale with galaxy two point correlation functions is currently the most promising approach to detect dark energy at early times. A number of ongoing and future experiments will measure the BAO peak with unprecedented accuracy. We show based on a set of N-Body simulations that the matter distribution is anisotropic out to $\sim 150 h^{-1}\text{Mpc}$, far beyond the BAO scale of $\sim 100 h^{-1}\text{Mpc}$, and discuss implications for the measurement of the BAO. To that purpose we use alignment correlation functions, i.e., cross correlation functions between high density peaks and the overall matter distribution measured along the orientation of the peaks and perpendicular to it. The correlation function measured along (perpendicular to) the orientation of high density peaks is enhanced (reduced) by a factor of 2 compared to the conventional correlation function and the location of the BAO peak shifts towards smaller (larger) scales if measured along (perpendicular to) the orientation of the high density peaks. Similar effects are expected to shape observed galaxy correlation functions at BAO scales.

Subject headings: large-scale structure of universe — methods: numerical

1. INTRODUCTION

The Baryonic Acoustic Oscillations (BAO) constitute a characteristic feature within the large scale structure of the Universe and can serve as standard ruler for constraining the properties of dark energy (e.g., Blake & Glazebrook 2003; Linder 2003; Seo & Eisenstein 2003; Wang 2006; McDonald & Eisenstein 2007; Seo & Eisenstein 2007; Seo et al. 2008, 2009; Kazin et al. 2012). The BAO in the baryon-photon fluid of the pre-recombination era imprint the sound horizon distance at decoupling as a typical scale in the matter correlation function or power spectrum (Peebles & Yu 1970; Sunyaev & Zeldovich 1970; Eisenstein & Hu 1999; Bashinsky & Bertschinger 2002). These oscillations were detected in the cosmic microwave background (e.g., Page et al. 2003) and in the spatial distribution of galaxies (Eisenstein et al. 2005; Cole et al. 2005) and have been confirmed by a number of subsequent studies (e.g., Percival et al. 2007; Cabré & Gaztañaga 2009; Sánchez et al. 2009; Percival et al. 2010; Reid et al. 2010; Kazin et al. 2010).

The next generation of large galaxy surveys, like the Panoramic Survey Telescope & Rapid Response System (Pan-STARRS, Kaiser et al. 2002), the Dark Energy Survey (DES, The Dark Energy Survey Collaboration 2005), the Baryonic Oscillation Spectroscopic Survey (BOSS, Schlegel et al. 2009), BigBOSS (Schlegel et al. 2011), the Hobby Eberly Telescope Dark Energy Experiment (HETDEX, Hill et al. 2004) and the space based Euclid mission (Cimatti et al. 2009), will cover volumes much larger than current datasets, allowing for much

more accurate determinations of the BAO.

In the two-point correlation function the BAO are visible as a unique broad and quasi Gaussian peak (Matsubara 2004). However, the determination of the shape and location of the peak may be affected by sample variance (Cabré & Gaztañaga 2009; Martínez et al. 2009; Kazin et al. 2010; Cabré & Gaztañaga 2011), non linear effects and the bias of the tracer galaxy population (Smith et al. 2003; Crocce & Scoccimarro 2006; Angulo et al. 2008; Crocce & Scoccimarro 2008; Seo et al. 2008). These difficulties lead Prada et al. (2011) to suggest to use the zero-crossing of the two point correlation located at $\sim 130 h^{-1}\text{Mpc}$ as standard ruler instead of the peak location. Yet, several observations do not show the theoretically predicted zero-crossing at all (Martínez et al. 2009; Kazin et al. 2010). At this stage it is unclear whether this discrepancy is caused by systematic effects or cosmic variance or whether it represents a challenge for the concordance ΛCDM model (Sylos Labini et al. 2009; Sánchez et al. 2009; Kazin et al. 2010).

One basic assumption for interpretation of the BAO measurements is that the matter distribution is isotropic at the relevant scales ($\sim 100 h^{-1}\text{Mpc}$). In this work we use alignment correlation functions (Paz et al. 2008; Faltenbacher et al. 2009) to show that the amplitudes of the two-point correlation function measured along the orientations of the high density peaks are larger than those derived from spherically averaged (conventional) clustering analysis out to scales of $\gtrsim 150 h^{-1}\text{Mpc}$ and discuss possible effects on measurements of the BAO.

2. METHODOLOGY

We use a set of large scale dark matter simulations which follow the evolution of the cosmic density field including its collapse into high density peaks. Based on their orientations we compute the alignment cross correlation function with the over all mass distribution out to

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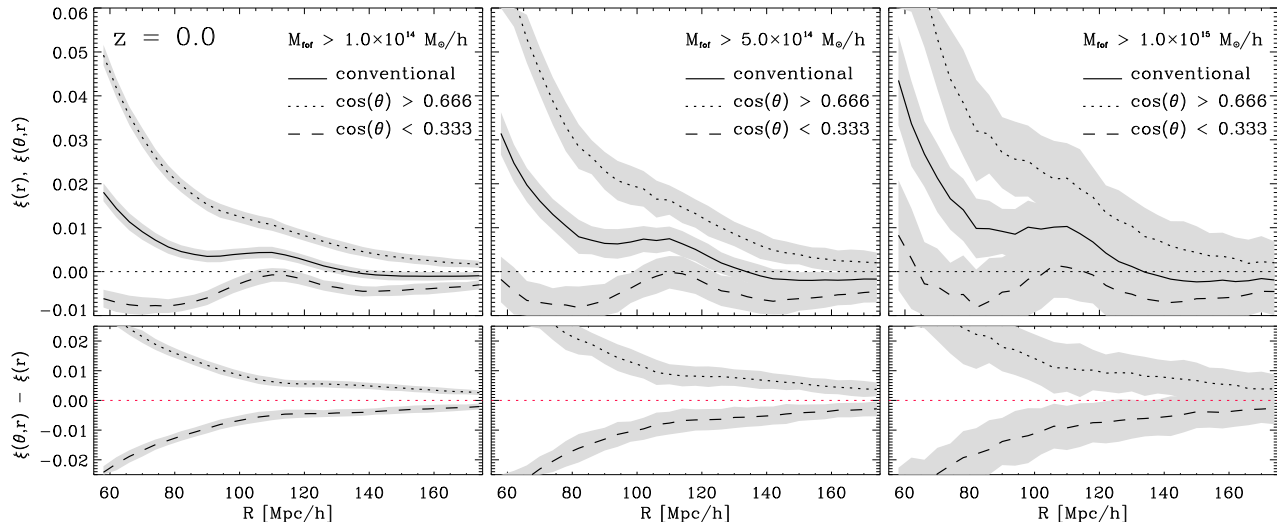


FIG. 1.— *Upper panels*: 3 dimensional two point cross correlation functions between FoF groups of the indicated mass and the overall matter density field represented by 10% random subset of all simulation particles. Solid lines show the *conventional* correlation functions. Dotted and dashed lines show the *alignment* correlation functions along and perpendicular to the orientations of the FoF groups, respectively. *Lower panels*: Difference between conventional and alignment correlation functions above. The shaded areas in the upper and lower panels give the cosmic variance. Poisson errors are negligible and are not shown here.

$\sim 200 h^{-1}\text{Mpc}$. In this section we briefly discuss the simulations, the computation of density peak orientations and the definition of the alignment correlation function.

2.1. Simulations

We used GADGET-2 (Springel 2005) to carry out 50 $1 h^{-1}\text{Gpc}$ -simulations based on the same concordant ΛCDM cosmology but different realizations of the initial density field. The total volume of the ensemble is almost 70 times larger than the volume used for the detection of the BAO signal by Eisenstein et al. (2005). The cosmological parameters correspond to those used for the *Milennium Simulation* (Springel et al. 2005): matter density parameter, $\Omega_M = 0.25$; cosmological constant term, $\Omega_\Lambda = 0.75$; power spectrum normalization, $\sigma_8 = 0.9$; spectral slope, $n_s = 1$; and Hubble parameter, $h = 0.73$. For each run 320^3 particles are used resulting in a mass resolution of $2.11 \times 10^{12} h^{-1}M_\odot$ for the dark matter particles. A Plummer-equivalent softening of $80 h^{-1}\text{kpc}$ was employed. An analysis based on a much lower force resolution showed very similar results.

2.2. Orientations of high density peaks

Density peaks are identified by using a friends-of-friends (FoF, Davis et al. 1985) group-finder by linking parameter $b = 0.2$ times the mean particle separation. In each realization there are about 30,000 FoF-groups with masses greater than $10^{14} h^{-1}M_\odot$. The orientations are derived by evaluating the eigenvalues of the second moment of the mass tensor. In the following the direction of principal axis associated with the largest eigenvalue is referred to as the (3D) orientation of the density peak. Observationally 3D orientations are difficult to determine, therefore, we also use projected orientations. These are determined by collapsing the mass distribution of the density peak along the line of sight (here equivalent to the z -axis) and, consecutively, computing the eigenvectors of inertia tensor for the two dimensional mass distribution. Despite the poor force resolution the orientations of the

density peaks are expected to trace the large scale tidal field well (see below).

2.3. Alignment correlation functions

Two-point correlation functions, $\xi(r)$, are a primary tool for quantifying the clustering properties of cosmological structures (e.g. Peebles 1980). We employ an extension of the *two-point cross-correlation function* which can be used to quantify spatial alignment of objects in one sample with respect to orientations assigned to the objects in the other sample (see, Paz et al. 2008; Faltenbacher et al. 2009; Schneider et al. 2011). Given a sample of objects in question (Sample Q), a sample of reference objects (Sample R) and a random sample (Sample \mathcal{R}) we can define the *alignment two point cross correlation function*

$$\xi(\theta, r) = \frac{N_R}{N_{\mathcal{R}}} \frac{QR(\theta, r)}{Q\mathcal{R}(\theta, r)} - 1, \quad (1)$$

where r indicates the distance, θ , is the angle between the orientation of the objects in Sample Q and the line connecting to objects in either of the two other samples. N_R and $N_{\mathcal{R}}$ are the number of points contained in the reference and random sample, $QR(\theta, r)$ and $Q\mathcal{R}(\theta, r)$ are the counts of cross pairs between the indicated samples for given θ and r . The conventional correlation function is the average of the alignment correlation function over the full range of θ values.

Taking symmetries into account the value of θ ranges from zero (along the orientation of the main object) to 90 degrees (perpendicular to its orientation). Thus, higher amplitudes of the alignment correlation functions at small values of θ indicate that the reference objects are more likely to be aligned along orientation of the main objects. In contrast, higher amplitudes at larger angles indicate that the reference objects are more likely to be located perpendicular to the orientation of the main objects.

We employ the alignment correlation functions, more exactly, the average of the alignment correlation function

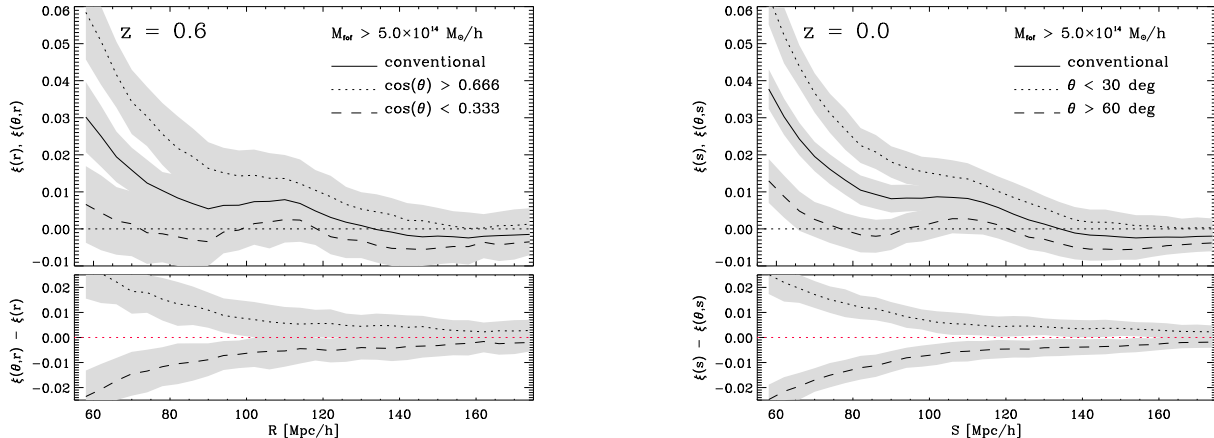


FIG. 2.— *Left panel:* Same as middle panel in Fig. 1 for a redshift of $z = 0.6$. *Right panel:* Same as middle panel in Fig. 1 but using projected orientations and redshift space separations (at $z = 0$).

within given angular ranges, to quantify the large-scale alignment between the matter distribution in the Universe and the orientation of high density peaks ($M_{Fof} \geq 10^{14} h^{-1} M_{\odot}$). The reference samples are generated from 10% random subsets of the overall particle distributions. If real-space correlations are considered we use the three dimensional orientation and separation vector to determine θ . Alternatively, if observational consequences are discussed we use projected orientations but still 3D distances since the effects of reshift-space distortions are small.

3. RESULTS

In this section we present our findings for the alignment correlation functions in real- and redshift-space and for redshifts $z=0$ and 0.6 .

Fig. 1 shows the conventional and alignment two point cross correlation functions (upper panels) and the residuals of the alignment correlation functions about the conventional correlation function (lower panels) employing different lower mass cuts (1×10^{14} , 5×10^{14} and $1 \times 10^{15} h^{-1} M_{\odot}$) for the high density peaks in the main sample. Solid lines show the conventional correlation functions. Dotted and dashed lines represent the correlation functions along and perpendicular to the orientations of the density peaks. The gray regions represent the cosmic variance. Interestingly, the cosmic variance in the lower panels is slightly smaller, this is because the differences between conventional and alignment correlation functions are independent of their absolute values. To check for systematic or numerical errors we have repeated the above analysis with randomly interchanged orientations within each realization. In this case we do not detect any significant difference between the conventional and alignment correlation functions.

The left panel of Fig. 2 displays conventional and alignment correlation functions for density peaks with masses larger than $5 \times 10^{14} h^{-1} M_{\odot}$ at $z = 0.6$. The right panel of Fig. 2 represents the correlation functions based on projected orientations. Here, the angles used to select the pairs along and perpendicular to the orientations of the density peaks are computed between the projected orientations and the projected distance vectors. Distances are computed in redshift space using the distant observer

approximation. In this case the differences in the amplitudes between the conventional and the alignment correlation functions are somewhat reduced but still significant beyond the BAO scale.

In conclusion, the alignment correlation function between dark matter density peaks with masses $\gtrsim 10^{14} h^{-1} M_{\odot}$ and the overall matter distribution reveals anisotropies at scales larger than $150 h^{-1} \text{Mpc}$ far beyond the BAO scale. The difference between conventional correlation functions and correlation functions measured along and perpendicular to the orientations of the peaks is most pronounced for the most massive peaks in real-space at $z = 0$. But it remains visible at earlier time and also if projected orientations are used.

4. DISCUSSION

The findings presented here are based on N-Body simulations however qualitative similar effects are expected to shape the observed galaxy correlation functions at scales up to $150 h^{-1} \text{Mpc}$. Potential observational implications are:

- *Large-scale anisotropy and structure of two point correlation functions:* Our results indicate that matter is distributed anisotropically out to separations far larger than the BAO scale. At any given pair separation the conventional correlation function is the average of the alignment correlation function over the whole range of θ . We find that the alignment correlation function measured along high density peaks does not fall below zero (for separations $\leq 150 h^{-1} \text{Mpc}$) which is counterbalanced by negative amplitudes at much smaller separations for measurements perpendicular to it. At the BAO scale galaxy two point correlation functions can be interpreted as the average of a more highly clustered component along the direction of high density peaks and a less clustered component perpendicular to it.
- *Shape and location of the BAO peak:* At BAO scales the amplitudes of the correlation functions between high density peaks and the overall matter distribution are significantly higher if measured along the orientation of the peaks. In this case the BAO peak is composed of a hump on top of the declining but still positive correlation function. The signal perpendicular to the orientations is dom-

inated by the BAO hump itself with negligible underlying clustering signal. The location of the BAO peak is found at somewhat smaller (larger) scales if measured parallel (perpendicular) to the orientation of high density peaks. For the measurements along the density peak orientations the BAO hump is transformed into a plateau-like feature. If the survey volume is dominated by large filamentary structures the shape of the conventional correlation function should be close to that found for the parallel signal shown here. This may relate to a study by Kazin et al. (2010) who find no apparent peak in 6% of their mock samples.

- *Zero crossing and large scale power:* Several publications report the non-detection of zero-crossing out to scales of $250 h^{-1} \text{Mpc}$ which indicates (unexpected) large scale power (e.g., Martínez et al. 2009; Kazin et al. 2010; Sylos Labini et al. 2009). We find similar results for the correlation functions measured along the orientations of high density peaks. Furthermore, the alignment cross correlation function measured along the orientations of high density peaks at $z = 0.6$ shows zero-crossing in contrast to the behavior at $z = 0$. The WiggleZ redshift-space correlation function at $z = 0.6$ (Blake et al. 2011) shows a crossover as well. Whether these analogies are coincidental remains to be explored in future work.

- *Direct measurement of anisotropy:* With the advent of enormous cluster catalogs (e.g., Hao et al. 2010; Gilbank et al. 2011) it should in principle be possible to

directly measure the large scale anisotropies with alignment correlation functions if cluster orientations can be determined with sufficient accuracy. An anisotropy signal may even be extracted simply by using orientations of the cluster central luminous red galaxies because the orientations of central galaxies and host systems are correlated (Faltenbacher et al. 2009; Okumura et al. 2009; Schneider et al. 2011).

- *Improvement of BAO measurements:* If the directional effects reported here are observable it would be worthwhile considering to measure the BAO peak perpendicular to the orientations of galaxy clusters (or luminous red galaxies) since in this direction the BAO peak is better confined.

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